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THE PREPARATION AND PROPERTIES OF ZIRCONIA-TOUGHENED ALUMINA

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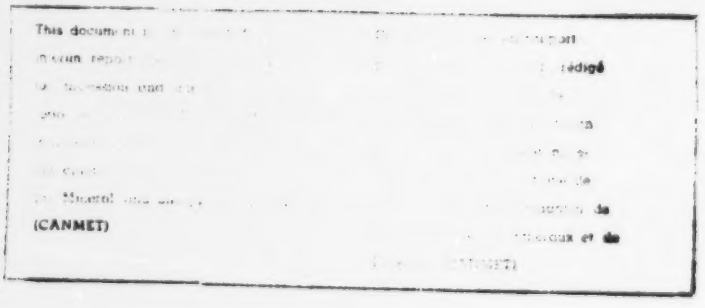

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THE PREPARATION AND PROPERTIES OF ZIRCONIA-TOUGHENED ALUMINA

by

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ABSTRACT

The synthesis of precursor powders and their subsequent conversion into zirconia toughened-alumina ceramics are described. The effects of different starting alumina raw materials on the properties of the product are discussed.

Keywords: Tough Ceramics; Zirconia-toughened Alumina; Alumina-zirconia Composites.

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PRÉPARATION ET PROPRIÉTÉS DE L'ALUMINE RENFORCÉE À L'OXYDE DE ZIRCONIUM

par

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RÉSUMÉ

La synthèse de poudres précurseurs et leur conversion subséquente en céramiques à base d'alumine renforcée à l'oxyde de zirconium sont décrites. Les effets de différentes matières premières alumineuses sur les propriétés du produit sont examinés.

Mots-clés: céramiques résistantes; alumine renforcée à l'oxyde de zirconium; composites alumine-oxyde de zirconium.

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INTRODUCTION

Ceramics have many very attractive material properties such as high strength and wear resistance, high temperature stability and corrosion resistance, high melting point, extreme hardness and stiffness, and retention of strength to very high temperatures. These properties place them in a highly advantageous position with respect to metals, in numerous structural applications where wear resistance, high temperature strength and corrosion resistance are of prime importance. Although many of the traditional ceramics have the above-mentioned properties, they all have one common weakness, viz., brittleness or low fracture toughness. (Fracture toughness is a measure of resistance to crack length extension under applied stress). The result of this brittleness is that when conventional ceramics are subjected to bending stress, they break catastrophically without any prior warning when the stress exceeds the bend strength. The impact strength of ceramics is also quite low. The implications of these weaknesses, if traditional ceramics are to be used in a structural application such as in an airplane jet engine turbine, are obvious. Metals on the other hand have relatively high fracture toughness and they yield under stress so that signs of the onset of failure will usually be evident long before catastrophic failure. Also, if one of the turbine blades breaks, it will not take the rest of them with it.

For many years, material scientists and ceramists have been aware of the brittleness problems and also of the potential of ceramics to advantageously replace metals for high temperature structural applications, if only their toughness could be improved. A considerable amount of research work has been carried out in making toughened ceramics and several approaches have been tried with varying levels of success. Most of the toughening enhancement techniques involve the use of a second phase in various morphological forms in a matrix of the parent ceramic. The morphological variations of the second phase could be whiskers, fibres, flakes or other forms. When using whiskers and fibres, the toughening effect is similar to that of glass fibre in resin-fibre glass or graphite fibre in resin-graphite fibre composites or to that of the steel wire or

bars in reinforced concrete. The influence of flakes is also similar. The mechanism of toughening with a second phase may involve several processes such as crack deflection, crack termination or blunting, interphase sliding/pull-out, etc. Micro-pores or pre-existing microcracks also can act like a second phase in toughening by a crack termination mechanism, but at the expense of material strength. (In the crack termination mechanism, a propagating crack stops at a pre-existing pore or crack and the crack has to be re-initiated before it can extend further, and the energy required for crack initiation is generally much higher than that for crack growth - this phenomenon manifests as increased fracture toughness).

One of the recent developments in toughened ceramics has been the discovery of the special effect of finely divided zirconia as a second phase in a hard matrix. This effect is caused by a special feature of zirconia (which few other materials possess), viz., that its high temperature crystalline forms (tetragonal and cubic) transform into the room temperature stable monoclinic form with an expansion in volume when cooled from a high temperature. When the zirconia is dispersed in a matrix, on cooling the expansion to form the monoclinic phase is opposed by the matrix, with the result that part of the zirconia (depending on its particle size) retains the tetragonal symmetry. In areas where the tetragonal to monoclinic transformation has occurred, the matrix forms microcracks and increases the fracture toughness to some degree. In areas where the zirconia stays as tetragonal (under pressure), the tetragonal to monoclinic transformation will occur only when the pressure exerted by the matrix on the zirconia is released, and if this is caused by an extending crack in the material, the crack will be blunted at that location. The toughening caused by this process is called zirconia-transformation toughening. Calculations have shown that such a mechanism can increase the fracture toughness of a material substantially (1-4).

Any zirconia-compatible ceramic material can be toughened by the transformation mechanism by the incorporation of fine zirconia, and zirconia itself can be toughened by the process. Partially stabilized zirconia (PSZ) is an example and has been one of the earliest materials discovered in the system (5). Zirconia-toughened alumina (ZTA) (6), mullite (7,8) and silicon nitride (9) are other examples. Based on cost-performance criteria,

zirconia-toughened alumina is one of the most promising materials in the transformation-toughened systems. Under proper processing conditions increases in fracture toughness by a factor of 2 over that of pure alumina ceramics have been reported (6,10).

Fused cast alumina-zirconia has been in use commerically for abrasive applications for several decades (11-15). Although the alumina-zirconia manufactured by the fusion casting process is a tough ceramic, the process is not practical for the fabrication of ceramic forms required for structural applications. The reasons for this are the problems related to thermal conductivity, heat transfer and shrinkage that come into play during the fusion casting of the very high temperature melts (temperatures of over 2000°C). Hence the traditional ceramic processing techniques of powder preparation, forming and sintering/hot-pressing are the routes available for the fabrication of objects with zirconia-toughened alumina ceramics.

One of the inherent problems with traditional ceramic processing techniques is that the materials so prepared lack the microstructural/microchemical homogeneity that is required of high-strength, high-temperature, structural ceramics. It is these microstructural/microchemical properties that most often differentiate a traditional ceramic from an advanced ceramic. Thus, a traditional ceramic when specially processed can become an advanced ceramic such as the modern high-temperature, high-strength ceramics that include silicon carbide, silicon nitride, zirconia, alumina, etc.

The most important of the steps involved in ceramic processing is the preparation of the precursor powder. It is this stage that determines the ultimate microstructural/microchemical characteristics of the prepared ceramic. Some of the important variables in this step are, the physics and chemistry of the raw materials (e.g. state of comminution, particle size distribution, the chemical reactions involved to produce the required compositions and the purity of reactants) and the method used for the preparation of the precursor powder, especially when it is a mixture. Traditional ball-mill techniques cannot be expected to produce a microscopically homogeneous powder mixture for the precursor; other techniques such as spray-drying, freeze drying, attrition milling and gel-processing are more appropriate.

The objective of the present study was to investigate the effect of different starting raw materials on the properties of alumina-zirconia ceramics when the precursor powders are prepared by a commercially feasible spray-drying process.

EXPERIMENTAL METHODS

Raw Materials

Three sources of alumina were used. They were, aluminum sulphate (C.P.), gibbsite (Alcan H-1) and RC-172 (Reynolds) alumina. For zirconia, zirconium hydroxide slurry prepared by the hydrolysis of zirconyl chloride was used as the source. Magnesium oxide (C.P) was employed as a stabilizer for tetragonal zirconia in some of the experiments.

Spray-Drying Procedure

A Buchi 190 Mini Spray-dryer was used for the preparation of the reactant powder mixtures. The spray-drying technique was chosen for this study because it is capable of producing homogeneous powder mixtures and the process is commercially feasible. Aqueous solution/slurries of the reactants prepared in appropriate strengths were used for the spray-drying.

The gibbsite-zirconia slurry was prepared by mixing the H-1 alumina and zirconium hydroxide slurry in the required proportions, milling the mixture with zirconia balls in a plastic bottle for 0.5 h and filtering through a 60 mesh (0.25 mm) screen to remove particles of the plastic from the system. (The plastic contamination clogs up the spray-dryer nozzle during spray-drying). The resultant slurry was constantly stirred magnetically until the spray-drying operation was completed.

The aluminum sulphate-zirconia and RC-172 alumina-zirconia slurries were also prepared by the same techniques used for the gibbsite-zirconia system. In the case of aluminum sulphate, however, the sulphate was first dissolved in a minimum amount of water before mixing it with the zirconium hydroxide slurry.

Synthesis of the Precursors by Calcination

The spray-dried powders were calcined at appropriate temperatures in order to form the precursor material by the reaction and/or decompostion of the reagents in the mixtures. The completion of the reaction was ascertained by measuring the weight loss sustained by the samples as a function of temperature, until the weight loss reached a constant value. The calcination products were characterized by X-ray diffraction.

Forming of Cylindrical Green Discs

After calcination, the powders were hand-ground in an alumina mortar and pestle, and discs were fabricated by uniaxially pressing the powder in steel dies. Discs of two different diameters were fabricated, one set in a 1.25 cm die and the other in a 3.80 cm die. A pressure of 140 MPa was used in both cases. In some instances, in order to make acceptable green discs (discs without any cracks which can be handled without breaking), it was necessary to mix the powder with varying amounts of PVA binder solution before the pressing operation. After drying, the green density of the discs was determined by measuring the diameter, thickness and mass. The binder, if any, was then burned off by slowly heating the discs at a rate of about 3°C/min to 600°C in air and holding for about 20 min.

Sintering

The discs were sintered at temperatures between 1580 and 1650°C inside platinum dishes for varying intervals of time. Conditions for obtaining a product of high density (98%+ when possible) were determined from temperature-time-density data.

Characterization of Products

The sintered products were characterized by density measurement, X-ray diffraction analysis (identification of phases and determination of tetragonal zirconia content), SEM (microstructural analysis), and

measurement of the mechanical properties - Young's modulus (elastic property) and modulus of rupture (MOR) (bend strength). The mechanical properties were measured by using a device designed at CANMET for supporting the disc at three points on a circle 2.54 cm in diameter and applying a load at the centre. A photograph of this equipment is shown in Fig. 1. Circular discs approximately 3 cm in diameter and 0.4 cm in thickness were used for these experiments. The load and displacement parameters were measured using an Instron strength-testing machine in conjunction with a load cell and dial gauge. Methods described by Timoshenko (16) were used for calculating the Young's modulus and MOR.

RESULTS AND DISCUSSION

Characteristics of Precursor Powders

Calcination of the spray-dried powders is expected to yield a mixture of alumina and zirconia. Depending on the raw materials and calcination temperature, the precursor powders produced could be either nearly amorphous or mixtures of various crystrallographic forms of alumina and zirconia. The possible forms of alumina are the gamma-type modifications and alpha-alumina. For zirconia, although the room temperature stable form is only the monoclinic allotrope, the tetragonal form also may be present depending on particle size (17,18) and the presence of a stabilizer such as MgO.

X-ray analysis of the calcination products showed the above discussed behaviour of the system. After calcination at 800°C, the powders made from gibbsite and zirconium hydroxide slurry were nearly amorphous; they showed only broad peaks which may be considered as belonging to gamma-alumina and tetragonal zirconia precursors. When calcined at 1300°C, the powders contained monoclinic and tetragonal forms of zirconia and alpha-alumina. However, the powders made using RC-172 alumina and zirconium hydroxide showed the presence of alpha-alumina at all calcination temperatures (because RC-172 is alpha-alumina) together with poorly crystallized tetragonal zirconia at temperatures below about 1000°C and a mixture of tetragonal and monoclinic zirconia at 1300°C.

The thermal decomposition of the gibbsite-zirconium hydroxide mixture and RC 172-zirconium hydroxide mixture (in approximately 2 g batches) could be completed at 600°C in about 2 h. Although zirconium hydroxide and aluminum sulphate decompose individually at 500 and 770°C respectively, their mixture required calcination at about 1000°C for complete reaction in the same amount of time. (The weight loss behaviour of aluminum sulphate-zirconium hydroxide mixtures when heated at various temperatures is shown in Table I). This must be due to the kinetics involved in the large mass loss associated with the decomposition of the aluminum sulphate.

Sintering Behaviour of the Various Compositions Made With Different Starting Materials

1. Gibbsite and Zirconium Hydroxide

The effects of sintering time and sintering temperature on the densification of the powders made from gibbsite (H-1) and zirconium hydroxide resulting in 10, 15 and 20 vol% of zirconia in the final product are illustrated in Table II. The theoretical densities of the three compositions calculated from the densities of alpha-alumina and monoclinic zirconia are, respectively, 4.16, 4.26 and 4.35 g/mL. Although the sintered density of all the compositions increases with an increase of sintering time and temperature, none of them densifies fully in the range studied. The highest densities obtained at 1650°C in 3h are only about 81% for the 10 vol% zirconia product and about 86% for the 15 and 20 vol% zirconia compositions.

2. Aluminum Sulphate and Zirconium Hydroxide

The sintering behaviour of the powders prepared from spray- dried aluminum sulphate-zirconium hydroxide mixtures is shown in Table III. Only two compositions (7.5 and 15 vol% zirconia-alumina) were investigated in this system. The theoretical sintered densities for these compositions are, respectively, 4.11 and 4.26 g/mL. At a sintering temperature of 1650°C,

both compositions attain a maximum sintered density of about 94.6% of theoretical in a sintering time of 0.25 h. Increased sintering time up to 2 h seems to have a detrimental effect on the density for the 7.5 vol% zirconia product, and practically no influence on the 15 vol% product. Lower sintering temperatures (1615 and 1580°C) also lower the sintered density.

3. RC 172 Alumina and Zirconium Hydroxide

In Table IV are presented the sintering characteristics of two alumina-zirconia precursor powders prepared by spray-drying a slurry containing Reynolds RC-172 alumina and zirconium hydroxide. Excellent densities, some that are over 98% of theoretical, are obtained by sintering the calcined powders at 1650°C for 0.5 to 1.0 h. At 1615 and 1580°, the densities are lower for the same sintering time intervals.

4. Aluminum Sulphate, Zirconium Hydroxide and Magnesium Oxide

The purpose of incorporating MgO into the composition is to partially stabilize tetragonal zirconia to various levels, thereby increasing the tetragonal zirconia content of the system even at increased zirconia crystal size. The powders were calcined at 1200°C prior to pressing into discs of about 3.75 cm diameter. Preliminary experiments revealed that a sintering temperature of 1650°C was too high for the system, because the discs warped and cracked after sintering. A temperature range of 1580 to 1615°C, however, appeared to be satisfactory. The sintering properties of powders prepared in the system at two zirconia concentrations (7.5 and 15 vol%) and three MgO concentrations (5, 10 and 15 mol% of the zirconia) are presented in Table V (A). The discs were sintered for 1 h at the temperatures indicated in the Table.

None of the discs in this system sinters to high density under the normally suitable conditions of the experiments. The highest density realized in the 7.5 vol% zirconia-5mol% MgO system is only about 81% of theoretical and in the 15 vol% zirconia-15 mol% MgO it is about 86% of theroetical.

Although MgO is considered to be a sintering aid in alumina systems, it is not clear why the presence of MgO is detrimental in this case when the alumina is produced from aluminum sulphate. In the absence of MgO, much higher densities are obtained (cf. Table III).

5. RC-172 Alumina, Zirconium Hydroxide and Magnesium Oxide

The results of the sintering experiments, when the aluminum sulphate in the previous section is substituted by RC-172 alumina, are given in Table V (B). The densification in this case is remarkable in that densities over 99% that of theoretical are obtained on sintering these powders at 1580 to 1615°C for 1 h.

Tetragonal Zirconia Content of the Various Products

X-ray diffraction analysis of the various sintered products made from spray-dried gibbsite and zirconium hydroxide showed that their tetragonal zirconia contents were quite low. The amounts of zirconia in the tetragonal form were respectively, 12, 6 and 0.3% of the total, for the products containing 10, 15 and 20 vol% of zirconia. For the products made from aluminum sulphate and zirconium hydroxide, however, the tetragonal zirconia content was very high - the 7.5 vol% zirconia-alumina product contained 65 to 79% of the zirconia in the tetragonal form while the 15 vol% zirconia-alumina contained 48 to 54% zirconia as tetragonal. At the 7.5 vol% level of zirconia, the tetragonal zirconia content of the product was not influenced by sintering temperature (1580 to 1650°C - 2 h) or by sintering time (0.25 to 2 h at 1650°C) significantly. On the other hand, the 15 vol% zirconia product, though not highly sensitive to the same temperature change, is greatly influenced by the sintering time - the tetragonal zirconia content decreases from about 50% to about 18% with an increase in sintering time from 0.25 to 2 h at 1650°C. Table VI illustrates these points. The very high tetragonal zirconia content of the products made from aluminum sulphate and zirconium hydroxide indicated that a high degree of transformation toughening is possible in this system even without the addition of any tetragonal zirconia stabilizing agents.

The alumina-zirconia products made from spray-dried RC-172 alumina-zirconium hydroxide mixtures also retained a considerable fraction of the zirconia in the tetragonal form after sintering. The tetragonal zirconia content of the various compositions in this system under various sintering conditions are listed in Table VII. It is almost independent of both sintering time (0.25 to 2 h at 1650°C) and sintering temperature (1580 to 1650°C) at the 7.5 vol% level of zirconia, but is slightly decreased by both increased sintering time and temperature at 15 vol% zirconia. Also, the fraction of tetragonal zirconia is considerably more in the 7.5 vol% composition than in the 15 vol% material, similar to the case with the products from aluminum sulphate and zirconium hydroxide. The increased tetragonal content of the lower zirconia concentration must be attributed to the larger fraction of finer zirconia particles that is possible when a reduced amount of zirconia is dispersed in the same volume of the alumina matrix.

The incorporation of 5 to 15 mol% MgO per mole of zirconia in the mixtures did not show any significant effect on the tetragonal zirconia content of the products either at the 7.5 or the 15 vol% levels of zirconia. In the case of both aluminum sulphate based compositions and the RC-172 alumina based mixtures, there was a slight drop in the tetragonal zirconia content at the 7.5 vol% zirconia level, but there was a slight increase at the 15 vol% composition. The reason for the decrease of tetragonal zirconia content with addition of MgO is not clear.

Strength and Elastic Modulus Measurements

The modulus of rupture (MOR) and the Young's modulus of the materials fabricated from the MgO-containing compositions were determined using the equipment and procedures described in the Experimental Section and are reported in Table VIII. The equations:

$$s = \frac{P\ \{\ (1+v)\ (0.485 \times \log\ (a/h) + 0.52) + 0.48\}}{h^2} \quad \text{and}$$

$$E = \frac{0.754 \times P \times a^2}{w \times h^3}$$

where s = strength (MOR)
P = Load
v = Poisson's ratio
a = Diameter supported
h = Thickness
E = Young's modulus and
w = displacement at the centre of the disc

were used for the calculations. Corrections were applied to the measured displacement values in the calculation of Young's modulus, in order to account for the deformation of the testing equipment.

A cursory glance at Table VIII reveals that the Young's modulus and strength of the products made using RC-172 alumina as the alumina source are quite consistent. The strength data on the products made using aluminum sulphate, however, show a large degree of scatter. This scatter must be attributed to the wide variations in the sintered densities of these products. Also, the strength and Young's modulus of the discs fabricated using RC-172 alumina are higher than those of discs made using aluminum sulphate, which again can be related to the consistently high densities of the former materials.

Considering the products from RC-172 alumina, the strength and Young's modulus in this system appear to be independent of the MgO content, but inversely related to the zirconia content. At 7.5 and 15 vol% zirconia, the average Young's modulii are about 257 and 208 GPa respectively. From individual Young's modulii and volume fractions of the alumina and zirconia, the upper and lower limits of the Young's modulii of the resultant composites can be calculated from the equations (19):

$$E_u = E_1V_1 + E_2V_2$$
$$1/E_L = V1/E_2 + V_2/E_2$$

where E_u = the upper limit of Young's modulus (Voigt)
E_L = the lower " " (Reuss)
E_1 = Young's modulus of the material of vol. fraction V_1
and E_2 = " " " " " V_2

Using the values of Young's modulii of 365 and 150 GPa respectively for alumina andd zirconia, the upper and lower limits are calculated to be 332 and 300 GPa for the 15 vol% zirconia-alumina product and 350 and 330 GPa for the 7.5 vol% zirconia-alumina. The measured values are, thus, approximately 25 and 35% less than theoretical for the 7.5 and 15 vol% zirconia products respectively. This difference must be attributed to the effects of microcracking of the alumina-zirconia products caused by the expansion accompanying the partial transformation of tetragonal zirconia to the monoclinic form during cooling, after sintering. The fact that the difference is more in the higher (15 vol%) zirconia product reinforces this argument.

The literature value for the strength of sintered alumina ceramics is about 210 MPa. Measurements made on sintered samples of alumina fabricated in the laboratory gave approximately 226 MPa for the strength, showing that the test methods were satisfactory.

The measured average strengths of the alumina-zirconia compositions are respectively, 394 and 337 MPa for 7.5 and 15 vol% zirconia-alumina (MgO) products. Strength increases respectively of about 75% and 49% are thus achieved at the 7.5 and 15 vol% zirconia content. As discussed under the section on Young's modulus, microcracking associated with the transformation of the tetragonal zirconia into the monoclinic form must be responsible for the lower strength increase at the higher zirconia content. Although the strength improvement achieved in this investigation is not as high as that for hot-pressed alumina-zirconia products (6), there is a cost advantage in the simple atmospheric-pressure sintering method. Also, these strength values are comparable to those reported by others on similarly processed materials (20).

Toughness

Toughness measurements have not been made on the various specimens that were prepared. A Tukon hardness tester has been set up in the laboratory for the determination of fracture toughness of ceramic materials by the indentation technique. During the strength testing, there have been indications that some of the specimens had high fracture toughness, because they did not break instantly at the yield point, but continued to support the load as shown in the strength test data in Fig. 2.

CONCLUSIONS

The starting raw materials have a marked influence on the properties of sintered alumina-zirconia ceramics. Products containing large proportions of tetragonal zirconia may be prepared by processing powders obtained by spray-drying mixtures (slurries) of zirconium hydroxide with aluminum sulphate or Reynolds RC-172 alumina (respectively over 75 wt% with aluminum sulphate and over 60 wt% with RC-172 alumina). The incorporation of MgO up to 15 mol% of the zirconia does not have a strong effect on the tetragonal zirconia content in these systems. Alumina-zirconia products made from calcined gibbsite and zirconium hydroxide yield very little tetragonal zirconia.

Of the three alumina raw material sources investigated, RC-172 alumina yields the densest products, aluminum sulphate the next best and the calcined gibbsite the poorest. The fracture strength (MOR) of the products is strongly related to their densities. Alumina-zirconia ceramics considerably stronger than alumina are produced from the RC-172 alumina-zirconium hydroxide raw material system.

The Young's modulii of the products are below the theoretically calculated values and it is attributed to residual porosity, and microcracking caused by the tetragonal to monoclinic zirconia transformation.

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REFERENCES

1. Evans, A.G. and Heuer, A.H. "Transformation Toughening in Ceramics; Martinsitic Transformation in Crack-Tip Stress Fields"; J. Amer. Ceram. Soc. 63: 241-48; 1980.

2. Porter, D.L., Evans, A.G. and Heuer, A.H. "Transformation Toughening in Partially Stabilized Zirconia (PSZ)"; Acta Metall. 27: 1649; 1979.

3. Porter, D.L. and Heuer, A.H. "Mechanisms of Toughening in Partially Stabilized Zirconia (PSZ)"; J. Amer. Ceram. Soc. 60: 183-84; 1977.

4. Claussen, N. "Stress Induced Transformation of Tetragonal Zirconia Particles in Ceramic Matrices"; J. Amer. Ceram. Soc. 61: 85-86; 1978.

5. Garvie, R.C., Hannik, R.H. and Pasco, R.T. "Ceramic Steel?"; Nature 258: 703-4; 1975.

6. Claussen, N. "Fracture Toughness of Alumina with an Unstabilized Zirconia Dispersed Phase"; J. Amer. Ceram. Soc. 59: 49-51; 1976.

7. Claussen, N. and Jahn, J. "Mechanical Properties of Sintered, in situ-Reacted Mullite-Zirconia Ceramics"; J. Amer. Ceram. Soc. 63: 228-29; 1980.

8. Yuan, Q-M, Tan, J-Q and Jin, Z-G "Preparation and Properties of Zirconia-Toughened Mullite Ceramics"; J. Amer. Ceram. Soc. 69: 265-67; 1986.

9. Claussen, N. and Jahn, J. "Mechanical Properties of Sintered and Hot-Pressed Si_3N_4 - ZrO_2 Composites"; J. Amer. Ceram. Soc. 63: 228-29; 1980.

10. Ruhle, M., Claussen, N. and Heuer, A.H. "Transformation and Microcrack Toughening as Complementary Processes in Zirconia-Toughened Alumina"; J. Amer. Ceram. Soc. 69: 195-97; 1986.

11. Marshall, D.W. and Roschuk, S.J. "Fused Alumina-Zirconia Abrasives"; U.S. Pat. 3,181,939 assigned to Norton Co., 1965.

12. Watson, G.R. and Rowse, R.A. "Zirconia-Alumina Abrasive Grain and Grinding Tools"; U.S. Pat. 3,891,408 assigned to Norton Co., 1975.

13. Patchett, J.E. and Quinan, J.R. "Coated Abrasive Material Comprising Alumina-Zirconia Abrasive"; U.S. Pat. 3,893,826 assigned to Norton Co., 1975.

14. Patchett, J.E., Kuriakose, A.K. and Van Loan, P.R. "Alumina-Zirconium Oxide Abrasive Material"; Ger. Pat. 2,458,685 assigned to Norton Co., 1975.

15. Kuriakose, A.K. and Beaudin, L.J. "Tetragonal Zirconia in Chilled Cast Aluminum-Zirconia"; J. Can. Ceram. Soc. 46: 45-50; 1977.

16. Timoshenko, S. in "Theory of Plates and Shells"; McGraw-Hill Book Company, Inc., New York, pp. 76 & 271, 1940.

17. Garvie, R.C. "Occurrence of Metastable Tetragonal Zirconia as a Crystallite Size Effect"; J. Phys. Chem, 69: 1238-43; 1965.

18. Garvie, R.C. "Stabilization of the Tetragonal Structure in Zirconia Microcrystals"; J. Phys. Chem. 82: 218-24; 1978.

19. Kingery, W.D. in "Introduction to Ceramics"; John Wiley and Sons, New York, pp. 773-776, 1954.

20. Krell, A., Blank, P. and Weiss, T. "Influence of Microcracking and Homogeneity on the Mechanical Behaviour of (Al_2O_3+ZrO_2) Ceramics"; J. Mater. Sci. 22: 3304-08; 1987.

Table I. Weight Loss Data on the Thermal Decomposition of Aluminum Sulphate–Zirconium Hydroxide Powder Mixtures

Calcination Temperature °C	600	800	1000	1200
Weight Loss, %	29.02	36.40	76.53	76.84

Table II. Sintering Data on Powders Made From H-1 Alumina (Gibbsite) and Zirconium Byroxide

Composition (Vol%)		Green Density	Sint. Temp.	Sint. Time	Sint. Density
Al_2O_3	ZrO_2	g/mL	°C	h	g/mL
90.0	10.0	1.80	1600	0.5	2.67
"	"	1.76	"	1.0	2.73
"	"	1.80	"	2.0	2.89
"	"	1.78	"	3.0	3.01
"	"	1.81	1625	0.5	2.80
"	"	1.79	"	1.0	3.05
"	"	1.78	"	2.0	3.29
"	"	1.81	"	3.0	3.33
"	"	1.78	1650	0.5	3.04
"	"	1.80	"	1.0	3.08
"	"	1.79	"	2.0	3.34
"	"	1.81	"	3.0	3.36
85.0	15.0	1.80	1600	0.5	2.71
"	"	1.79	"	1.0	2.84
"	"	1.78	"	2.0	3.01
"	"	1.81	"	3.0	3.08
"	"	1.78	1625	0.5	2.96
"	"	1.82	"	1.0	3.19
"	"	1.76	"	2.0	3.23
"	"	1.78	"	3.0	3.30
"	"	1.82	1650	0.5	3.15
"	"	1.80	"	1.0	3.26
"	"	1.82	"	2.0	3.47
"	"	1.79	"	3.0	3.65
80.0	20.0	1.86	1600	3.0	3.39
"	"	1.80	1625	3.0	3.46
"	"	1.87	1650	0.5	3.38
"	"	1.81	"	1.0	3.52
"	"	1.82	"	2.0	3.57
"	"	1.85	"	3.0	3.74

Table III. Sintering Data on Powders Made From Aluminum Sulphate and Zirconium Hydroxide After Calcination at 1200°C.

Composition (Vol%)		Green Density	Sint. Temp.	Sint. Time	Sint. Density
Al_2O_3	ZrO_2	g/mL	°C	h	g/mL
92.5	7.5	1.81	1650	0.25	3.89
"	"	1.86	"	0.50	3.79
"	"	1.87	"	1.00	3.77
"	"	1.86	"	2.00	3.87
"	"	1.97	1615	"	3.81
"	"	1.92	1580	"	3.67
85.0	15.0	1.89	1650	0.25	4.03
"	"	1.86	"	0.50	3.99
"	"	1.79	"	1.00	4.02
"	"	1.78	"	2.00	3.97
"	"	1.83	1615	"	3.89
"	"	1.78	1580	"	3.90

Table IV. The Sintering Characteristics of Powders Made From RC-172 Alumina and Zirconium Hydroxide

Composition (Vol%)		Green Density	Sint. Temp.	Sint. Time	Sint. Density
Al_2O_3	ZrO_2	g/mL	°C	h	g/mL
92.5	7.5	2.33	1650	0.25	3.81
"	"	2.36	"	0.50	3.87
"	"	2.29	"	1.00	4.02
"	"	2.40	"	"	3.93
"	"	2.36	"	2.00	3.96
"	"	2.42	1615	1.00	3.83
"	"	2.34	1580	"	3.64
85.0	15.0	2.13	1650	0.25	4.04
"	"	2.09	"	0.50	4.20
"	"	2.12	"	1.00	4.17
"	"	2.10	"	2.00	4.11
"	"	2.18	1615	1.00	4.13
"	"	2.03	1580	"	4.10

Table V. The Sintering Behaviour of Powders Prepared From Spray-dried Aluminum sulphate, Zirconium Hydroxide and Magnesium Oxide (A) and RC-172 Alumina, Zirconium Hydroxide and Magnesium Oxide (B).

Composition			Green Density	Sint. Temp.	Sint. Density
Al_2O_3 (vol%)	ZrO_2 (vol%)	MgO (mol%/ZrO_2)	g/mL	°C	g/mL
A					
92.5	7.5	5.0	1.53	1600	3.03
"	"	"	1.53	1615	2.49
"	"	10.0	1.63	1580	2.68
"	"	"	1.58	1600	2.31
"	"	"	1.55	1615	2.82
"	"	15.0	1.85	1580	3.34
"	"	"	1.63	1600	2.83
"	"	"	1.63	1615	3.16
85.0	15.0	5.0	1.61	1580	2.86
"	"	"	1.63	1615	3.16
"	"	10.0	1.85	1580	3.34
"	"	"	1.63	1600	2.83
"	"	"	1.64	1615	3.03
"	"	15.0	1.63	1580	3.50
"	"	"	1.65	1600	3.66
"	"	"	1.61	1615	2.96
B					
92.5	7.5	5.0	2.25	1580	4.08
"	"	"	2.24	1600	4.05
"	"	"	2.16	1615	4.10
"	"	10.0	2.22	1580	4.07
"	"	"	2.20	1600	4.10
"	"	"	2.15	1615	4.06
"	"	15.0	2.13	1580	3.91
"	"	"	2.20	1600	4.02
"	"	"	2.22	1615	4.08
"	"	"	2.20	1650	3.85
85.0	15.0	5.0	2.31	1580	4.10
"	"	"	2.40	1600	4.22
"	"	"	2.18	1615	3.82
"	"	10.0	2.19	1580	4.08
"	"	"	2.13	1600	4.03
"	"	"	2.13	1615	4.08
"	"	15.0	2.30	1580	4.15
"	"	"	2.24	1600	4.18
"	"	"	2.29	1615	4.08
"	"	"	2.02	1650	3.60

Table VI. The Tetragonal Zirconia Contents of Alumina-zirconia Products When Fabricated From Spray-Dried Aluminum Sulphate-Zirconium Hydroxide Mixture

Composition (Vol%) Alumina	Zirconia	Sint. Temp. °C	Sint. Time h	% Tetragonal Zirconia
92.5	7.5	1650	0.25	69.5
"	"	"	0.50	70.1
"	"	"	1.00	78.1
"	"	"	2.00	65.8
"	"	"	"	78.9
"	"	1615	"	73.2
"	"	1580	"	66.7
85.0	15.0	1650	0.25	52.0
"	"	"	0.50	41.5
"	"	"	1.00	33.7
"	"	"	2.00	18.3
"	"	1650	0.25	48.4
"	"	1615	"	53.6
"	"	1580	"	54.3

Table VII. Tetragonal Zirconia Content of Products Made From RC-172 Alumina–Zirconium Hydroxide Mixtures

Composition Alumina	(Vol%) Zirconia	Sint. Temp. °C	Sint. Time h	% Tetragonal Zirconia
92.5	7.5	1650	0.25	50.5
"	"	"	0.50	51.1
"	"	"	1.00	57.2
"	"	"	2.00	55.1
"	"	"	1.00	52.1
"	"	1615	"	46.1
"	"	1580	"	50.0
5.0	15.0	1650	0.25	16.3
"	"	"	0.50	15.9
"	"	"	1.00	11.7
"	"	"	2.00	9.5
"	"	"	1.00	8.1
"	"	1615	"	11.3
"	"	1580	"	14.9

Table VIII. MOR and Young's Modulus of Alumina–Zirconia–Magnesia Ceramics as Measured on Discs Across a Diameter of 2.54 cm

Alumina Source	zirconia (vol%)	Magnesia (mol%/ZrO_2)	Young's Mod. (Aver.)* (GPa)	MOR (Average)* (MPa)
RC-172	7.5	5.0	249 (6)	397 (6)
"	"	10.0	241 (11)	395 (11)
"	"	15.0	281 (5)	389 (5)
"	15.0	5.0	217 (6)	337 (6)
"	"	10.0	208 (8)	317 (8)
"	"	15.0	199 (14)	356 (11)
AS**	7.5	5.0	200 (4)	150 (4)
"	"	10.0	179 (5)	112 (5)
"	"	15.0	223 (4)	284 (4)
"	15.0	5.0	180 (4)	190 (4)
"	"	10.0	205 (4)	171 (4)
"	"	15.0	194 (5)	213 (5)

* The number in brackets denotes the number of determinations.
** AS = Aluminum Sulphate

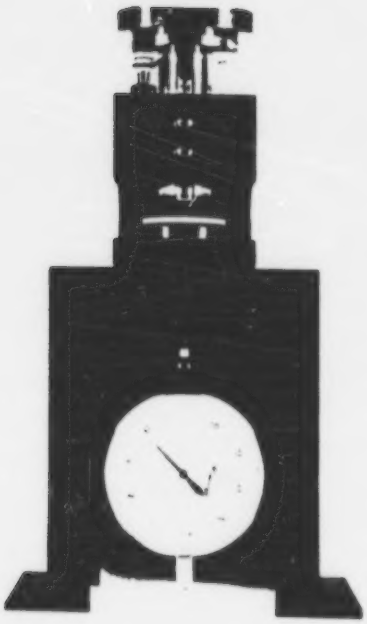

Fig. 1. Photograph of the equipment used for measuring Young's modulus and fracture strength of discs

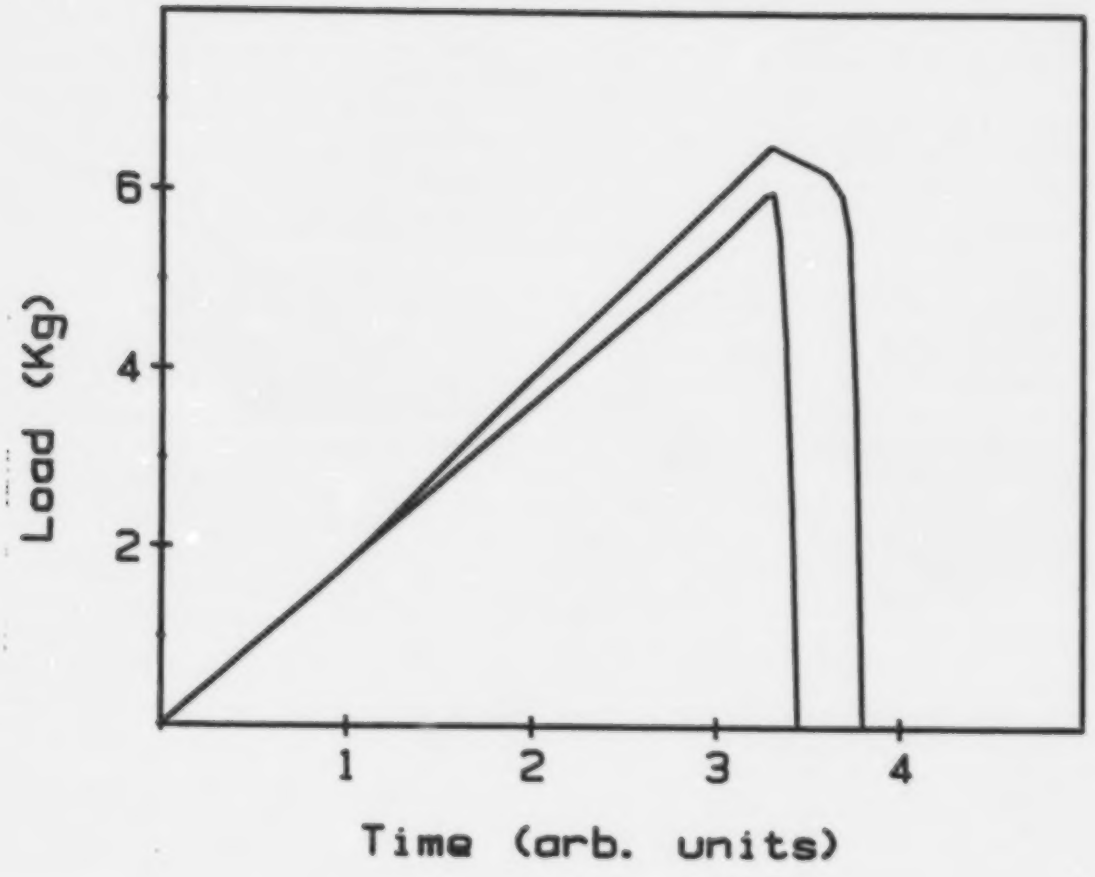

Fig. 2. Plot of applied load vs. time for two samples demonstrating low (curve A) and high (curve B) fracture toughness